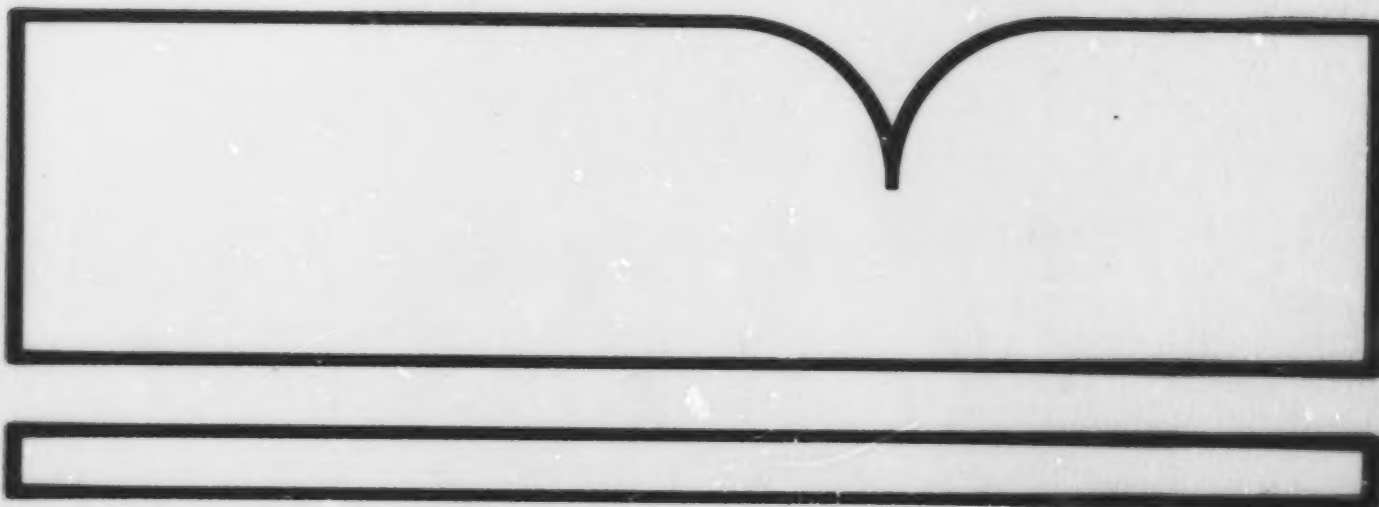


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Behavioural and Autonomic  
Thermoregulation in Hamsters during  
Microwave-Induced Heat Exposure

(U.S.) Health Effects Research Lab.  
Research Triangle Park, NC

1984



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## BEHAVIOURAL AND AUTONOMIC THERMOREGULATION IN HAMSTERS DURING MICROWAVE-INDUCED HEAT EXPOSURE\*

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**Abstract**—1. Preferred ambient temperature ( $T_a$ ) and ventilatory frequency were measured in free-moving hamsters exposed to 2450 MHz microwaves. A waveguide exposure system which permits continuous monitoring of the absorbed heat load accrued from microwave exposure was imposed with a longitudinal temperature gradient which allowed hamsters to select their preferred  $T_a$ . Ventilatory frequency was monitored remotely by analysing the rhythmic shifts in unabsorbed microwave energy passing down the waveguide.

2. Without microwave exposure hamsters selected an average  $T_a$  of 30.2°C. This preferred  $T_a$  did not change until the rate of heat absorption (SAR) from microwave exposure exceeded approx. 2 W kg<sup>-1</sup>. In a separate experiment, a SAR of 2.0 W kg<sup>-1</sup> at a  $T_a$  of 30°C was shown to promote an average 0.5°C increase in colonic temperature. Hamsters maintained their ventilatory frequency at baseline levels by selecting a cooler  $T_a$  during microwave exposure. In contrast, hamsters maintained at a  $T_a$  of 30°C (without a temperature gradient) underwent a sharp increase in ventilatory frequency compared to animals allowed to select their own  $T_a$ .

3. These data support previous studies suggesting that during thermal stress behavioural thermoregulation (i.e. preferred  $T_a$ ) takes precedence over autonomic thermoregulation (i.e. ventilatory frequency). It is apparent that selecting a cooler  $T_a$  is a more efficient and/or effective than autonomic thermoregulation for dissipating a heat load accrued from microwave exposure.

**Key Word Index**—2450 MHz; breathing rate; preferred  $T_a$ ; specific absorption rate; hamster; *Mesocricetus auratus*; thermoregulation.

### INTRODUCTION

Thermoregulation in homeotherms is achieved through behavioural and autonomic effectors. Many studies have shown that behavioural mechanisms are preferentially activated over autonomic systems (Ingram, 1975; Schmidt, 1978; Adair, 1976; Gordon, 1983a). For example, pigeons rely principally on behaviour to control skin and body temperature during extreme heat stress. Limiting the pigeon's behavioural response results in an increased body temperature and activation of respiratory heat loss (Schmidt, 1978). Microwave-exposed mice will preferentially seek a cooler ambient temperature ( $T_a$ ) rather than increase ventilatory frequency (Gordon, 1983a).

A waveguide-type microwave exposure system is a useful tool for thermal physiological studies because it permits remote, continuous monitoring of the rate of heat absorption in free-moving animals (Gordon, 1982a). This method is advantageous over indirect

methods where the animal must be killed to determine the level of heat absorption (Gordon, 1982b). By monitoring the level and/or rate of heat absorption one can more clearly describe the stimulus-response properties of the thermoregulatory system.

A 2450 MHz waveguide exposure system has been developed in our laboratory which permits exposure and monitoring of absorbed microwave energy as well as observing preferred  $T_a$  (Gordon, 1983a, b). Our laboratory has also developed a system for remote monitoring of ventilatory frequency in unrestrained rodents using microwave radiation (Gordon and Ali, 1984). Thus, this exposure system is ideal for studying the hierarchy of activation of behavioural vs autonomic thermoregulatory effectors. For example, exact quantities of microwave-induced heat can be delivered to the animal while its preferred  $T_a$  (i.e. a behavioural response) and ventilatory frequency (i.e. an autonomic response) are continuously monitored. In this study the breathing frequency (breaths min<sup>-1</sup>) and preferred  $T_a$  of free-moving golden hamsters are monitored during exposure to microwave radiation.

### MATERIALS AND METHODS

Animals used in the behavioural study were young adult, male, golden hamsters (*Mesocricetus auratus*) with a mean body weight of 120.6 ± 13.6 (SD)g. The animals were maintained at 5 per cage at 22°C under a 12:12 L:D photoperiod.

\*This paper has been reviewed by the Health Effects Research Laboratory, U.S. Environmental Protection Agency (EPA), and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use. Opinions expressed in this paper are those of the author and do not necessarily reflect official EPA opinion.

### Apparatus

A straight section of 2450 MHz waveguide was modified into a temperature gradient to observe the preferred  $T_b$  of hamsters during microwave exposure [for details, see Gordon (1983a, b)]. One end of the waveguide was immersed in a water bath thermostabilized to  $45 \pm 1^\circ\text{C}$ . The opposite end of the waveguide was immersed in a cold water bath set at  $13 \pm 1^\circ\text{C}$ . Forty-five 0.15 cm dia holes spaced 1.58 cm apart were drilled along the top and bottom of the waveguide. With the waveguide in a darkened room the position of the hamster was determined by noting where light from a fluorescent lamp did not pass through the holes.

A shuttle box,  $5.2 \times 6.8 \times 77.5$  cm ( $h \times w \times l$ ), made of 3.1 mm (1/8") Plexiglas was placed inside the waveguide. The box was perforated with holes to facilitate thermal equilibration with the waveguide. The hamster had free movement inside the shuttle box. Air dried with calcium anhydrite was pumped into the cool end of the waveguide at a flow rate of  $4.5 \text{ l min}^{-1}$ .  $T_b$  at different positions of the shuttle box was measured with thermocouples in the absence of microwave exposure. Temperature was normally not monitored inside the waveguide during microwave exposure. However, we have, on occasion, measured the temperature of the shuttle box during high-intensity microwave exposure and found that temperature increased by no more than  $0.1^\circ\text{C}$ . Further details on the waveguide exposure system (Gordon, 1982a) and shuttle box temperature gradient have been reported previously (Gordon, 1983a, b).

### Protocol

Naïve hamsters usually take several hours to adapt to the experimental conditions of the shuttle box and temperature gradient. Thus, it was necessary to use a small number of animals repeatedly to collect behavioural and physiological data with minimum variation. Four hamsters were used over a 36-day period. The first 14 days were used to accustom the animals to the temperature gradient and microwave exposure.

Experiments were run between 8 a.m. and 4 p.m. Monday to Friday. A hamster was tested during the morning or afternoon and then rested for 48 h before another test. Between experiments the shuttle box was washed in a detergent solution, rinsed and then dipped in a solution of 70% alcohol. This procedure was followed in an attempt to eliminate any olfactory cues that might affect thermoregulatory behaviour.

The shuttle box was placed in the waveguide and allowed to thermally equilibrate for 1 hr. A single hamster was placed inside the shuttle box at the cool end which was then sealed with a Plexiglass lid. After the hamster had been in the shuttle box for 30 min its position was determined at 5-min intervals for 30 min. At the end of the second 30 min period the microwave generator was activated at incident powers (i.e. measured at point of entry into waveguide) of 0, 0.076, 0.19, 0.38, 0.57, 0.76, 0.95, 1.14 and 1.52 W. Thirty minutes after the onset of microwave exposure the position of the hamster was measured at 5-min intervals for another 30 min. The animals were exposed to microwaves for a total time of 60 min. Thirty minutes after the termination of microwave exposure the position of the hamster in the shuttle box was determined.

### Breathing rate

The method for monitoring ventilatory frequency using microwave radiation will be described briefly [for further details see Gordon (1983a) and Gordon and Ali (1984)]. The technique is based on the principle that as the hamster inhales and exhales, its volume and, hence, absorption of microwaves changes concomitantly. To detect and record these small, rhythmic changes in adsorbed power the analogue d.c. output from the power meter monitoring transmitted power ( $P_{\text{trans}}$ ) was fed into a differential voltage

amplifier. The resultant output,  $dP_{\text{trans}}/dt$ , was recorded on a chart recorder as well as fed into a frequency counter to give a continuous recording of breathing frequency. An inflection in  $dP_{\text{trans}}/dt$ , which occurs with a transient drop in absorbed power is associated with expiration. The reverse situation occurs during inspiration. Any sudden movements by the animal causes shifts in transmitted power much greater than that evoked by breathing, hence, the hamsters must be relatively quiescent to record their breathing activities.

Ventilatory frequency was usually recorded during the first 30 sec of microwave exposure. These data, regardless of power level, were relatively low and were assumed to represent near-baseline conditions. That is, during the onset of high-intensity exposure the animal initially exhibited baseline breathing because it had not responded to the thermal stress of microwave exposure. Thirty minutes after the onset of microwave exposure ventilatory frequency was monitored at approx. 5-min intervals for the last 30 min of exposure. These data were used to represent the thermal effects of microwave exposure on ventilation.

To assess the effects of the temperature gradient on the sensitivity of ventilatory frequency to a microwave heat load, hamsters were placed in a waveguide thermostabilized to  $30^\circ\text{C}$  (i.e. their preferred  $T_b$ , see Fig. 1). They were exposed for 20 min to average whole body heat loads of 2.6 and  $5.2 \text{ W kg}^{-1}$ . Ventilatory frequency data were collected near the end of the 20 min exposure period.

### Calculation of microwave-induced heat load

Absorbed power was continuously recorded on a chart recorder. The average whole-body energy absorption rate, conventionally defined as the specific absorption rate (SAR), was calculated as mean absorbed power over 60 min of microwave exposure divided by the animal's weight and, hence, has the dimensions of  $\text{W kg}^{-1}$ . For further details on recording and calculation of SAR, see Gordon (1982a).

### Body temperature measurements

To determine the effects of microwave exposure on body temperature, direct body temperature measurements were taken on exposed animals. Seven, adult male hamsters were used repeatedly over a 20-day period. A waveguide system thermally stabilized at  $30^\circ\text{C}$  was used as described previously. Dry air was pumped into the system at a flow rate of approx.  $4.0 \text{ l min}^{-1}$ .

Individual hamsters were weighed and then placed into a Plexiglass cage which was placed into the waveguide. The mean weight of the hamsters was  $106 \pm 7.6$  (SD)g. Each hamster was allowed to become accustomed to the conditions of the waveguide for 1 h before microwave exposure after which the microwave generator was activated at one

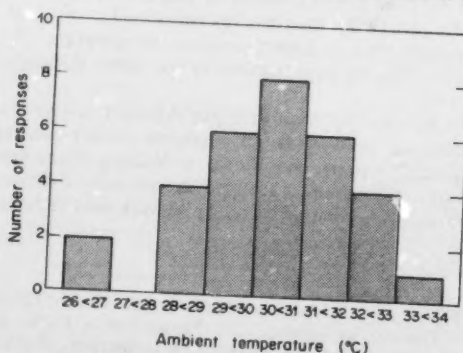


Fig. 1. Distribution of 4 golden hamsters in temperature gradient without microwave exposure. Each datum represents the average position of a hamster 30-60 min after being placed in the gradient;  $N = 31$ .

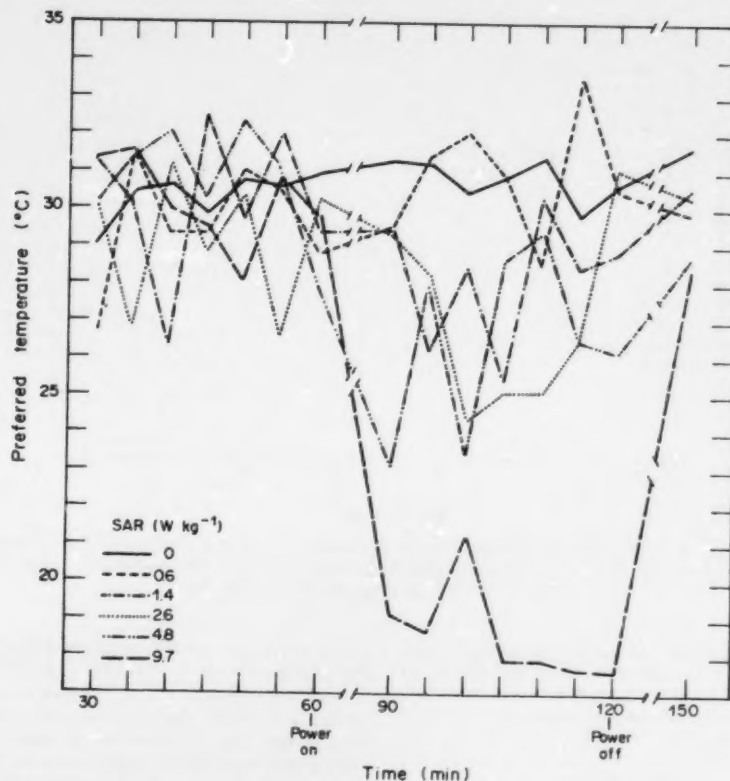


Fig. 2. Time-course of change in mean preferred  $T_a$  of hamsters exposed to specific absorption rates (SARs) of 0–9.7  $\text{W kg}^{-1}$ . Note that position in temperature gradient was not monitored during the first 30 min of the pre-exposure and exposure periods;  $N = 3-4$  for the points plotted.

power level for 30 min. Animals were exposed to SARs from 0 up to 9.0  $\text{W kg}^{-1}$ . At the end of the 30 min exposure time direct measurements of colonic temperature ( $T_{\text{col}}$ ) were taken with a Vitek temperature probe inserted 2.5 cm past the anal sphincter. Temperatures were taken as quickly as possible to avoid any rise in temperature due to stress

caused by handling. SAR was monitored during the 30 min exposure period on a chart recorder as described above.

#### Statistical analysis

In the behavioural experiments the relationship between preferred  $T_a$  and SAR was analysed using a repeated-

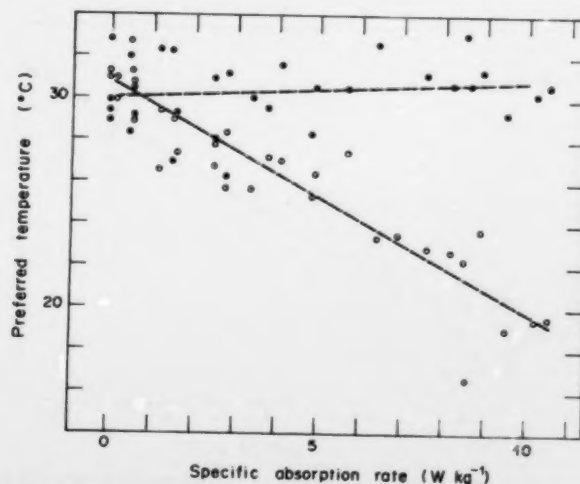


Fig. 3. Overall effect of SAR on preferred  $T_a$  of 4 golden hamsters. Each plotted point represents the average preferred  $T_a$  for each 30 min interval before (●) and during (○) microwave exposure;  $N = 31$ .

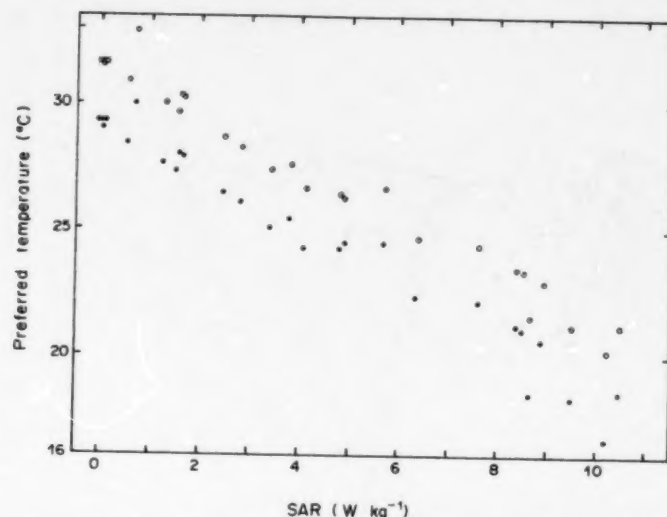


Fig. 4. Upper and lower 95% confidence intervals of preferred  $T_a$  during the last 30 min of microwave exposure as calculated by multiple linear regression. Confidence intervals were individually calculated for each of the 31 data points plotted in Fig. 3.

measures linear regression procedure. This method calculated 95% confidence intervals of each animal as affected the repeated-measures procedure. Body temperature and ventilatory frequency data were analysed using linear regression and students *t*-tests.

#### RESULTS

The distribution of the hamster's preferred  $T_a$  without microwave exposure is shown in Fig. 1. Most responses occurred at a  $T_a$  of 30–31°C with a range of 26–34°C. The average  $\pm$ SD of preferred  $T_a$  was  $30.2 \pm 1.6^\circ\text{C}$ .

Examples of the time-course of selection in preferred  $T_a$  during exposure to microwaves at average SARs of 0, 0.6, 1.4, 2.6, 4.8 and 9.7  $\text{W kg}^{-1}$  are shown in Fig. 2. Preferred  $T_a$  prior to microwave exposure

was variable but overall averaged approx. 30°C over the 30 min interval. SARs of 0 and 0.6  $\text{W kg}^{-1}$  caused little change in preferred  $T_a$ . Exposure to 1.4  $\text{W kg}^{-1}$  caused a transient decrease in preferred  $T_a$  between 90–105 min, however, during the last 15 min of exposure the animals returned to their pre-exposure preferred  $T_a$ . SARs of 2.6, 4.8 and 9.7  $\text{W kg}^{-1}$  induced more consistent decreases in preferred  $T_a$ .

A linear regression analysis of preferred  $T_a$  before and during microwave exposure vs SAR is shown in Fig. 3. There was a significant decrease in preferred  $T_a$  with increasing SAR ( $F = 185$ ,  $P < 0.0001$ ). To statistically analyse these data a multiple linear regression analysis was performed and 95% confidence intervals were calculated for each datum (Fig. 4). Using a  $T_a$  of 30°C as a cut-off point, which is the

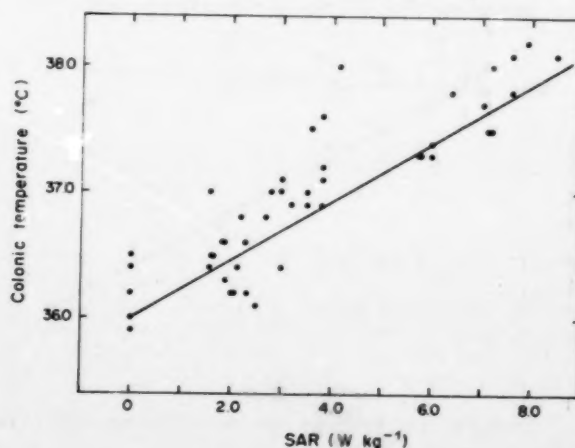


Fig. 5. Relationship between SAR and  $T_{\text{col}}$  in the golden hamster immediately after 30 min of microwave exposure. For sake of clarity not all data points were plotted at 0  $\text{W kg}^{-1}$ . Linear regression analysis:  $y = 0.23x + 36.1$ ,  $r = 0.88$ ;  $N = 50$ .

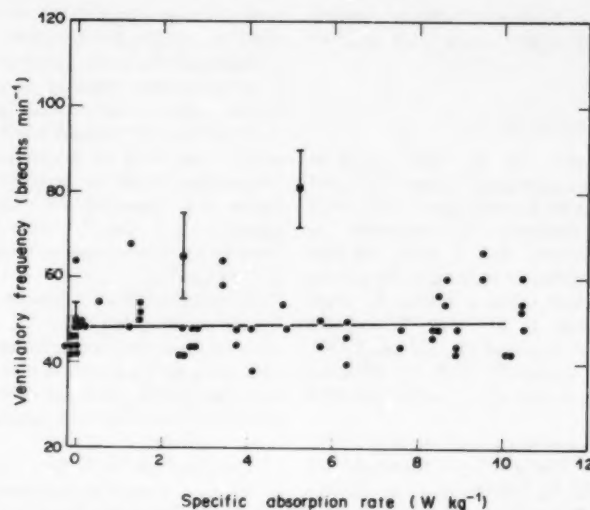


Fig. 6A. Ventilatory frequency of hamsters as a function of SAR while in the thermal gradient (●) and forced to remain at their preferred  $T_a$  of 30°C (■). Ventilatory frequency at SAR of 0 was determined by analysis of initial breathing frequency records at all 14 SAR exposures (see Materials and Methods). Ventilatory frequency was determined during the last 30 min of microwave exposure in temperature gradient. Linear regression analysis: without temperature gradient,  $y = 4.2x + 56.3$ ,  $r = 0.4$ ,  $N = 24$ ; with temperature gradient,  $y = 0.2x + 48.3$ ,  $r = 0.1$ ,  $N = 59$ .

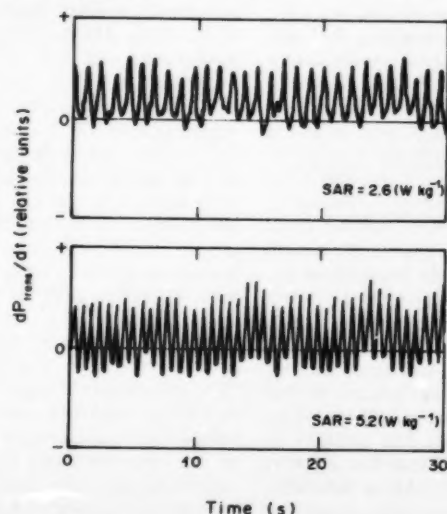


Fig. 6B. Example of breathing activity data collected in a hamster forced to remain at  $T_a$  of 30°C. Note elevated breathing rate with increasing SAR. Rise in  $dP_{\text{trns}}/dt$  associated with expiration and decrease in  $dP_{\text{trns}}/dt$  associated with inspiration.

preferred  $T_a$  without microwave exposure, the upper 95% confidence interval was below the cut-off  $T_a$  above a SAR of 2 W kg<sup>-1</sup>. This is inferred to be the threshold SAR where behavioural thermoregulation is significantly affected in the golden hamster.

There was a significant linear correlation ( $t = 13.6$ ,  $P < 0.005$ ) between SAR and  $T_{\text{col}}$  in hamsters exposed to microwaves at a  $T_a$  of 30°C (Fig. 5). At a SAR of 0 W kg<sup>-1</sup> the  $T_{\text{col}}$  was  $36.0 \pm 0.26$  (SD) °C. At a SAR of 2.0 W kg<sup>-1</sup>, which represents the threshold for affecting thermoregulatory behaviour, the  $T_{\text{col}}$ , estimated by regression, was 36.4°C.

During microwave exposure in the temperature gradient mean ventilatory frequency was 48–50 breaths min<sup>-1</sup> (Fig. 6A). There was no significant effect of SAR on ventilatory frequency during microwave exposure in the temperature gradient ( $t = 0.78$ ,  $P > 0.05$ ). However, when hamsters were forced to remain at their preferred  $T_a$  of 30°C, microwave exposure had a significant, positive effect on ventilatory frequency ( $t = 2.07$ ,  $P < 0.025$ ; Fig. 6A). An example of a ventilatory frequency recording from a hamster exposed at a  $T_a$  of 30°C is shown in Fig. 6B. In this individual, ventilatory frequency was

58 breaths  $\text{min}^{-1}$  at a SAR of  $2.6 \text{ W kg}^{-1}$  which increased to 86 breaths  $\text{min}^{-1}$  when SAR was increased to  $5.2 \text{ W kg}^{-1}$ .

#### DISCUSSION

At incident powers of 0 and  $0.076 \text{ W}$  ( $\text{SAR} = 0.6 \text{ W kg}^{-1}$ ) the preferred  $T_a$  was  $30.7$  and  $30.8^\circ\text{C}$ , respectively. At an incident power of  $0.19 \text{ W}$  ( $\text{SAR} = 1.4 \text{ W kg}^{-1}$ ), preferred  $T_a$  decreased to  $28.1^\circ\text{C}$ . Thus, we conclude that a SAR between  $0.6$ – $1.4 \text{ W kg}^{-1}$  causes sufficient heating to the golden hamster such that it will select a cooler  $T_a$  when exposed at its preferred  $T_a$  of  $30^\circ\text{C}$ . Taking the average between the no response vs response SARs, we conclude that the threshold SAR for affecting behavioural thermoregulation in the golden hamster is approx.  $2 \text{ W kg}^{-1}$ .

At a  $T_a$  of  $30^\circ\text{C}$  there was a linear increase in  $T_{\text{col}}$  with increasing SAR. The  $2 \text{ W kg}^{-1}$  threshold for affecting thermoregulatory behaviour (Fig. 4) was associated with a  $0.4^\circ\text{C}$  increase in  $T_{\text{col}}$  (Fig. 5). One should note that the behavioural and  $T_{\text{col}}$  effects of microwaves were assessed in two different experiments. However, the relations in Figs 4 and 5 suggest that a rising  $T_{\text{col}}$  or deep body temperature may be a cue which activates behavioural selection of a cooler  $T_a$  during microwave exposure.

The ventilatory frequency data show that when the hamsters are in the temperature gradient they will preferentially activate behavioural thermoregulation before autonomic regulation. That is, in the temperature gradient ventilatory frequency increased by only 2 breaths  $\text{min}^{-1}$  when SAR increased from 0 to  $10 \text{ W kg}^{-1}$ . However, when the hamsters were maintained at their preferred  $T_a$  of  $30^\circ\text{C}$  but without the option of selecting a lower  $T_a$ , ventilatory frequency increased by 27 breaths  $\text{min}^{-1}$  when SAR increased from 0 to just  $5.2 \text{ W kg}^{-1}$ . Thus, without the option of selecting a cooler environment the hamsters underwent a significant increase in ventilatory frequency in an apparent attempt to dissipate the microwave heat load.

The behavioural and breathing frequency data for the golden hamster follow a similar pattern to that demonstrated in the mouse (Gordon, 1983a). However, the mouse is comparatively less sensitive to microwave exposure. It was shown that BALB/c mice did not select a cooler  $T_a$  until the SAR at 2450 MHz exceeded  $7 \text{ W kg}^{-1}$ . When the mice were exposed at their preferred  $T_a$  of  $30^\circ\text{C}$  their ventilatory frequency did not increase until SAR exceeded approx.  $7 \text{ W kg}^{-1}$ . Mice were similar to hamsters in that during microwave exposure in the temperature gradient they maintained ventilatory frequency at baseline levels as a cooler  $T_a$  was selected. Hence, in both species the behavioural thermoregulatory response has precedence over the autonomic response during microwave exposure.

From the foregoing discussion it is apparent that behavioural thermoregulation by the hamster is more efficient or more effective than elevating ventilatory frequency for dissipating excess body heat accrued from microwave exposure. This is a reasonable assumption since most rodents, being non-panting mammals, have a relatively poor ability to dissipate

heat through respiratory water loss (Hart, 1971; Gordon, 1982b). For example, assuming that 2426 J is dissipated for each gramme of water evaporated, a 125 g hamster exposed to a SAR of  $5.0 \text{ W kg}^{-1}$  would have to evaporate an amount of water equal to 6% of its body weight per hour to dissipate 100% of the heat load by evaporation. Of course, some evaporation would occur by routes other than ventilation (e.g. insensible loss through skin, applying saliva to fur). On the other hand, given that the hamster has a minimal coefficient of heat exchange of  $0.62 \text{ W kg}^{-1}^\circ\text{C}^{-1}$  (Pohl, 1965), one would predict that the same  $5 \text{ W kg}^{-1}$  microwave heat load could be dissipated by selecting a  $8^\circ\text{C}$  cooler  $T_a$ . Therefore, with such an ineffective means of dissipating body heat through evaporation it is not surprising to find that the hamster will preferentially seek a lower  $T_a$  rather than increase its ventilatory rate during microwave exposure.

The threshold SAR of  $\sim 2.0 \text{ W kg}^{-1}$  at 2540 MHz to induce a change in thermoregulatory behaviour is similar to thresholds reported in the rat ( $1.0 \text{ W kg}^{-1}$ ) and squirrel monkey ( $1.1 \text{ W kg}^{-1}$ ) exposed to microwaves (Stern *et al.*, 1979; Adair and Adams, 1980). However, it may be difficult to compare the data of this study with previous work since the experimental conditions differed tremendously.

It is of interest to note that at the hamster's preferred  $T_a$  of  $30^\circ\text{C}$ , thermoneutrality for this species (Pohl, 1965; Hart, 1971), movement to a cooler environment did not occur until SAR exceeded  $\sim 2 \text{ W kg}^{-1}$  which is much less than the threshold reported for mice using similar experimental techniques ( $5.3$  to  $7.0 \text{ W kg}^{-1}$ ; Gordon, 1983a, b). The difference in threshold between mouse and hamster may be largely attributed to the difference in body mass and, consequently, the surface area/mass relation. Mice with a body mass of  $\sim 25 \text{ g}$  have a much greater rate of passive heat loss compared to a golden hamster with a body mass of  $\sim 125 \text{ g}$ . At a  $T_a$  of  $20^\circ\text{C}$  mice exposed to 2450 MHz microwaves underwent a  $0.8^\circ\text{C}$  increase in  $T_{\text{col}}$  at a SAR of  $22.2 \text{ W kg}^{-1}$  (Berman *et al.*, 1978). On the other hand, golden hamsters exposed to 2450 MHz microwaves at a  $T_a$  of  $22^\circ\text{C}$  underwent the same  $0.8^\circ\text{C}$  rise in  $T_{\text{col}}$  at a SAR of  $9 \text{ W kg}^{-1}$  (Berman *et al.*, 1982). Since activation of behavioural thermoregulation appears to be related to microwave-induced hyperthermia then it is not surprising, given the data of Berman *et al.*, that the hamster has a lower threshold SAR compared to the mouse. Of course, one should not rule out other possible factors such as differences in pelage density and the presence of the furless tail in the mouse which may enhance overall heat dissipation.

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